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EARLY ORDOVICIAN MAGMATISM IN THE NORTHERN CENTRAL IBERIAN ZONE (IBERIAN MASSIF): NEW U-Pb (SHRIMP) AGES AND ISOTOPIC Sr-Nd DATA

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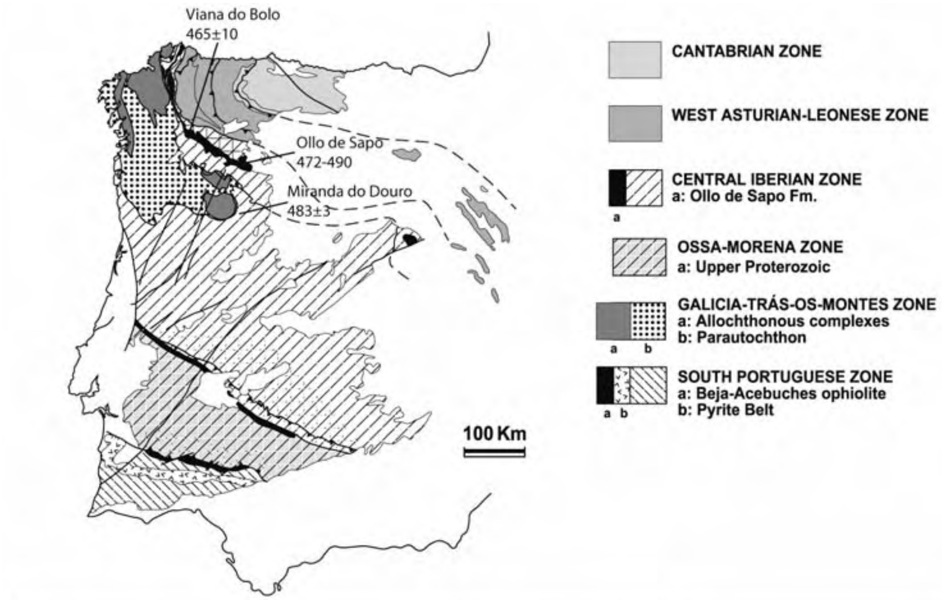
INTRODUCTION

In the Central Iberian Zone (CIZ), an important volume of terrigenous sediments was deposited during the Early Ordovician, among them, the widespread Armorican Quartzite. This formation outlines the Variscan orocline from the northwest to the central outcrops of the Iberian Massif (Fig. 1). Late Cambrian-Early Ordovician magmatism produced a great amount of crustal melts, giving rise to large bodies of aluminous granites and explosive volcanic rocks, the so-called Ollo de Sapo volcano-sedimentary formation (Hernández Sampelayo, 1922; Parga Pondal et al., 1964). Both lithologies formed during an acid magmatic episode derived from crustal melts, which is related to the birth of the Rheic Ocean (Navidad et al., 1992; Gebauer, 1993; Valverde Vaquero and Dunning, 2005; Díez Montes, 2007; Montero et al., 2007). There is evidence of intra-ordovician tectonic movements (Sardic event, Julivert et al., 1972) that originated unconformities at the base of the Early Ordovician series (Toledanic unconformity, Díez Balda et al., 1990; Pérez Estaún et al., 1991), and a passive margin sequence from Early Ordovician to Early Devonian. So far, there is no clear evidence for thermal metamorphism coeval with this important Ordovician magmatism in the CIZ.

In this paper, we report two new SHRIMP ages of augen orthogneisses from the Guadarrama Sierra (Spanish Central System) and new isotopic Sr-Nd data from orthogneisses and Ollo de Sapo volcanic rocks from the northern CIZ. We complete our dataset with data from other authors to obtain a geodynamic model for the early Ordovician crust in the CIZ.

GEOLOGICAL SETTING

The Ollo de Sapo Formation crops out in the core of a Variscan antiform in the limit between the West Asturian-Leonese and the Central Iberian zones (Julivert et al., 1972). It delineates an arc from northern



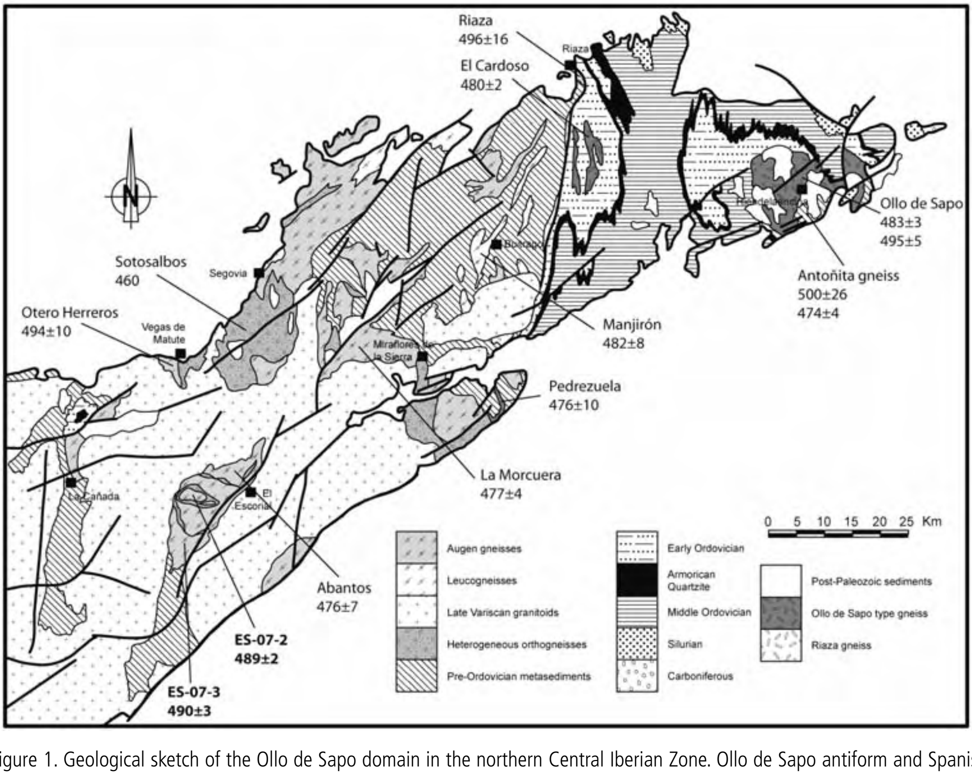


Figure 1. Geological sketch of the Ollo de Sapo domain in the northern Central Iberian Zone. Ollo de Sapo antiform and Spanish Central System. Ages of metagranitic orthogneisses and Ollo de Sapo volcanic rocks (in Ma) are distributed in different metamorphic Variscan massifs.

Galicia to the easternmost outcrops of the Spanish Central System (Hiendelaencina gneissic dome: Fig. 1). The Armorican Quartzite also outlines this structure and below it, the Ollo de Sapo Formation crops out at the lower part of the Tremadocian metasediments or interbedded within them. The volcano-sedimentary rocks were deformed and metamorphosed during the Variscan orogeny, varying in grade from the chlorite and biotite zones, where they show the characteristic blue quartz, to the Ms out-Kfs in zone, where they are migmatitic augen gneisses. It is formed by meta-dacitic and meta-rhyolitic explosive rocks and volcaniclastic sediments of greywacke composition; sub-volcanic meta-granite bodies are enclosed in the former (Navidad, 1978; Navidad et al., 1992; Díez Montes et al., 2004). Their characteristic aspect is a porphyroid rock with feldspar megacrysts of different size and blue subvolcanic quartz crystals embedded into a quartz–feldspathic matrix that show occasional relict of ignimbrite structures.

This Formation has been repeatedly dated by different methods, with results ranging from 618 Ma to 465 Ma (Lancelot et al., 1985; Wildberg et al., 1989; Gebauer, 1993). Recent U-Pb ages on zircon crystals offer more precise ages: ~480 Ma for Valverde Vaquero and Dunning, 2000; whereas Montero et al. (2007), dated the explosive rocks between 495 and 483 Ma, similar to the ages obtained by Díez Montes et al. (2010) for the intrusive metagranites (between 483 to 474 Ma). Based on inherited zircons some authors place Central Iberia to the east of the African Craton in the Early Ordovician (Díez Montes et al., 2010; Bea et al., 2010). This location is in agreement with the faunal data and the paleogeographic situation proposed by Gutiérrez Marco et al. (2002). This proposal contrasts with those where the location of the CIZ next to the West African Craton, based on TDM isotopic model ages and inherited zircon populations from sediments of the CIZ, put forward by Martínez Catalán et al. (2004), Fernández Suárez et al. (2000) and Ugidos et al. (2003).

The metagranitic augen gneisses represent an important volume of aluminous granitoids placed into a pre-Tremadocian sequence that crops out underlying the Ollo de Sapo Formation. They form massifs of different extension along the northern CIZ, small bodies in the northwestern Iberian Peninsula (Porto, Sanabria and Viana do Bolo), and massifs of kilometric extension in the Guadarrama Sierra (Spanish Central System, Fig. 1). They crop out from the biotite to moscovite out-Kfs in metamorphic zones, where they are migmatizated. The massifs are constituted by different compositional types, being the most frequent mesocratic and feldspar-rich augen gneisses, leucogneisses rimming the augen gneisses or forming independent massifs, and the banded gneisses are more frequent to the east of the Somosierra domain in the medium grade metamorphic zones. There is no contact metamorphism related to the intrusion of these rocks, but in several cases there are tourmaline rims in the contact with the medium grade metasediments.

Navidad (1979) and Navidad et al. (1992) point out, in the first whole-rock geochemical studies, the genetic similarity between the augen orthogneisses and the Ollo de Sapo volcanic rocks and suggest a crustal origin for them. Later, Valverde Vaquero and Dunning (2000) link both protoliths to a felsic magmatic belt active during the break-up of the Gondwanan margin and the birth of Iapetus Ocean.

Based on Rb-Sr isocrons, Vialette et al. (1987) ascribe ages of emplacement from 494 to 471 Ma, related to the Armorican Quartzite sedimentation. U-Pb ages show emplacement ages spanning from 482 to 468 Ma related to the Sardic *sensu lato* event (Lancelot et al., 1985; Gebauer et al., 1993; Valverde Vaquero and Dunning, 2000; Montero et al., 2007, Díez Montes et al., 2010). Regarding the ages present in the crust hosting these igneous rocks, Wildberg et al. (1989), based in inherited zircon populations, point out a protracted evolution during the Paleozoic from 540 Ma. Lancelot et al. (1985) cited Precambrian crustal components (2.4 and 2.0 Ga) that could be derived from the West Africa Craton, whereas Montero et al. (2007) found inherited zircon populations with ages between 0.85-0.90 and 0.7-0.65 Ga.

GEOCHRONOLOGY

Two orthogneiss samples from the El Escorial metamorphic massif (Spanish Central System: Fig. 1) were selected for SHRIMP analysis, including U-Pb geochronology and REE (rare earth elements) and elemental Hf determinations in zircon. Sample ES-07-2 corresponds to the so-called Santa María de la Alameda orthogneiss and its zircon grains are colorless to yellow, forming simple bipyramidal prisms with aspect ratios between 2:1 and 3:1. Under cathodoluminescence (CL) they usually display a moderately luminescent oscillatory zoning, with scarce xenocrystic cores. Sample ES-07-3 is a melanocratic augengneiss, locally known as the Robledo orthogneiss. Zircon from this sample is generally less colored and forms prisms with higher aspect ratios (4:1). There are also subrounded grains which are probably inherited. Under CL, the hand-picked zircons show oscillatory zoning.

Forty-seven analyses were carried out in sample ES-07-2, four of them are discarded because of their high common Pb or their inherited character. The remaining fourty-three are continuously distributed between 506 and 416 Ma. There are at least two possible explanations for this dispersion: lead loss or inheritance. Owing to the absence of inherited xenocrysts, we consider that the magmatic age of this sample is closer to the older end. Considering the twelve oldest analyses, the best estimate for the age is obtained from a group of eight analyses which yield a mean age of 489 ± 3 Ma, with a mean square of weighted deviation (MSWD) of 1.6.

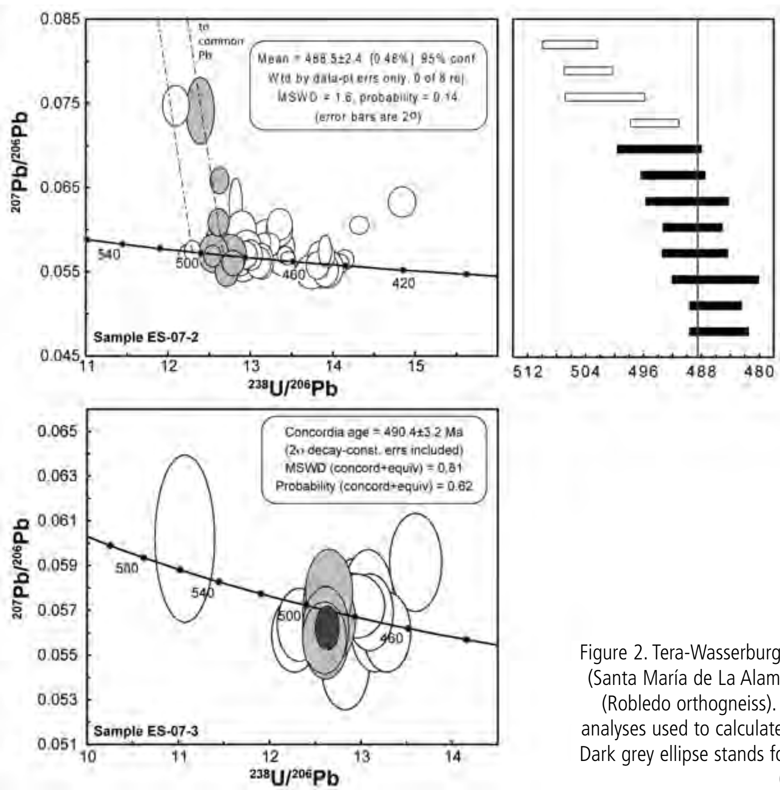


Figure 2. Tera-Wasserburg diagrams for samples ES-07-2 (Santa María de La Alameda orthogneiss) and ES-07-3 (Robledo orthogneiss). Light grey ellipses represent analyses used to calculate the age (mean or Concordia). Dark grey ellipse stands for Concordia age in sample ES-07-3.

In sample ES-07-3, eighteen analyses spread out between 506 and 456 Ma. The best statistical estimate for the crystallization age of this sample is obtained from six analyses that yield a concordia age of 490 ± 3 Ma (MSWD=0-81).

GEOCHEMISTRY

The Ollo de Sapo volcanic rocks and the metagranitic orthogneisses have been repeatedly analyzed in the last thirty years (Navidad, 1978, 1979; Navidad et al., 1992; Ortega et al., 1996; Díez Montes et al., 2004). Whole-rock geochemistry allows us to classify the volcanic rocks as dacite and rhyodacite tuffs of calc-alkaline affinity and the orthogneisses as aluminous granites. Both derived from melts enriched in potassium with trace elements normalized profiles showing a subduction geochemical signature marked by a Ta-Nb negative anomaly. This anomaly, in the case of volcanic rocks, has been interpreted as representative of a continental arc. Rare earth normalized profiles are fractionated with a negative anomaly in europium owing to the fractionation of plagioclase, which is characteristic of calc-alkaline melts.

New Sr-Nd isotopic data from the Ollo de Sapo Formation and the metagranitic orthogneisses are presented here. The Sr-Nd analyses were carried out at the Centro de Geocronología y Geoquímica Isotópica of the Complutense University of Madrid using the ID-TIMS method.

Metavolcanic and metagranitic orthogneiss samples show an important variation of $(^{87}Sr/^{86}Sr)_{490-470}$, spanning from 0.7068 to 0.7126 and the εSr between 8 and 123; contrastingly, the $(^{143}Nd/^{144}Nd)_{490-470}$ is more homogenous and the samples are concentrated in a little range, between 0.5117 and 0.5119, with high εNd values varying between -3 and -6. In a εSr, εNd diagram (Fig. 3a), the samples plot in the crustal provenance quadrant and they define a straight line suggesting mixing petrogenetic processes between juvenile melts and primitive arc-type isotopic signature related with their high eNd and crustal origin (Farmer and DePaolo, 1983). The plot $f_{Sm/Nd}$ versus εNd (Fig. 3b from DePaolo and Wasserburg, 1976), show a distribution from active to passive margins, but preferably in the latter geodynamical context.

With regard to the model ages, the εNd signature respect to the early Ordovician ages (Fig. 3c), shows a coincidence between the Ollo de Sapo and the metagranite values and their intersection with the CHUR evolution line point to a time span of the TCHUR ages between 0.7 and 1.6 Ga for the metagranites and from 1.0 to 1.5 for the Ollo de Sapo volcanic rocks suggesting a more protracted extraction period for the metagranitic than for the volcanic melts. TCHUR and provenance zircon ages are equivalent (Late Neoproterozoic and Mesoproterozoic), suggesting that the most probable sources for the Late Cambrian-Early Ordovician magmatism are melts from a Late Neoproterozoic crust essentially formed by a mixture of juvenile and Mesoproterozoic components.

INTERPRETATION AND CONCLUSIONS

Late Cambrian-Early Ordovician magmatism is constituted by aluminous metagranites intruded into pre-Early Ordovician sequences, and calc-alkaline explosive volcanic rocks are synsedimentary with Early Ordovician metasediments. The age of this magmatism varies in the northern CIZ between 490 and 470 Ma, being slightly previous and synchronous to the Armorican Quartzite *sensu stricto*.

Whole-rock geochemistry characterizes this magmatism as aluminous crustal melts intruded in an extensional geodynamic context. However all magmatic protoliths preserve a subduction signature from an orogenic arc and the rare earth profiles are in agreement with calc-alkaline melts.

Contrastingly, Sr-Nd isotopic data indicates inhomogeneous $^{87}Sr/^{86}Sr$ content, and the alignment of the samples in the graphs suggests mixing processes between different melts. The high and homogeneous εNd signature (between -2.8 and -5.8), suggest that juvenile magmas or melts from a young crust are involved in the source of this magmatism.

Finally, Neoproterozoic zircon and TCHUR ages (0.6-0.7 Ga) are always present in both protolith types along the CIZ, implying the most probable age of crust source. Additionally, mafic protoliths are scarce or absent in the Early Ordovician sequences. However, in the Eastern Iberian Massif (Navidad and Carreras, 1998; Castiñeiras et al., 2008) syn-sedimentary metabasites from E-MORB tholeiitic melts and aluminous metagranites with subduction signatures are present in the Ediacaran sequences, and in the southern CIZ there are mafic fragments with TDM of 650 Ma in Silurian breccias (López Guijarro et al., 2008). We consider that the youngest Neoproterozoic sequences formed by sediments with Mesoproterozoic and Paleoproterozoic components, with juvenile rocks emplaced in them, are the most probable crustal source for the Late Cambrian-Early Ordovician magmatism that is developed in an extensional geodynamic context during the opening of the Rheic Ocean.

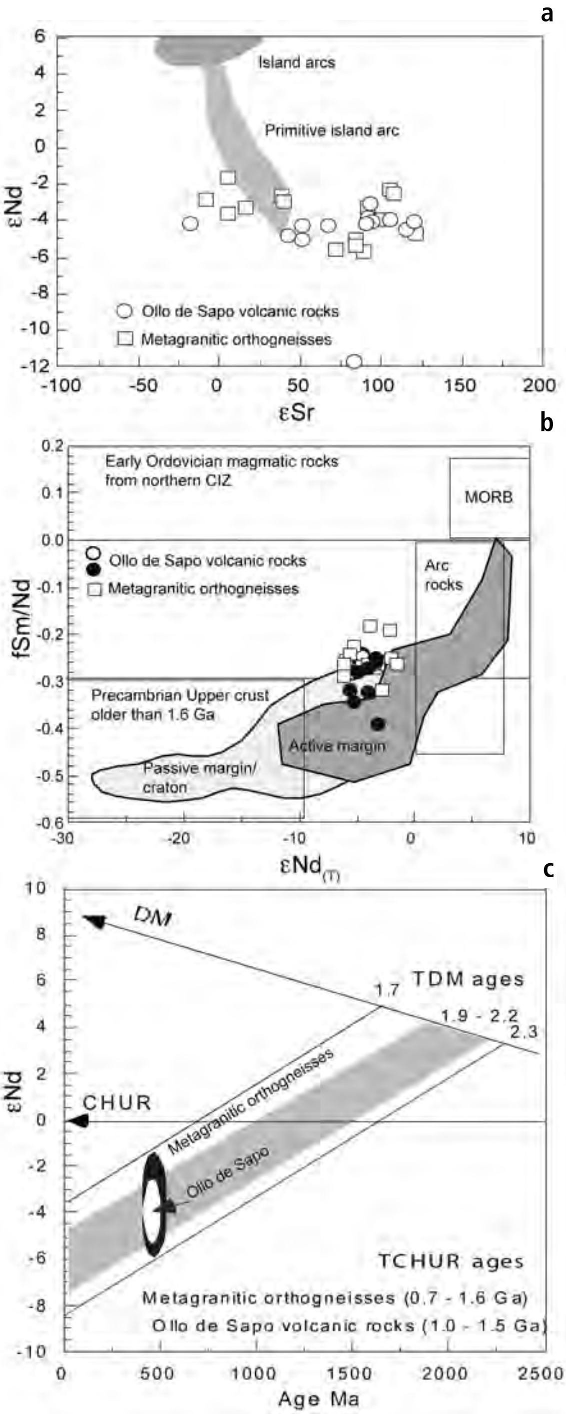


Figure 3. a, εSr– εNd binary diagram. Metagranitic orthogneisses and volcanic rocks samples draw an horizontal line of mixed processes. b, f $^{87}Sr/^{86}Sr$–εNd binary diagram with orogenic context for the CIZ magmatic rocks. c, εNd-age with CHUR and DM lines from DePaolo and Wasserburg (1976).The plot of samples are enclosed in the areas that intersected in CHUR and DM lines and marked the model ages.

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